Fig. 4 shows the case where the volume was kept constant. In this case the change of the behaviour of the moving striations when the temperature was raised was conspicuous.

The author wishes to express his hearty thanks to Prof. Sir Ernest Rutherford and Dr. Aston for their kind interest and guidance.

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# *The Magnetic Spectrum of the β-Rays Excited by γ-Rays.*

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In recent years, the photo-electric effect of light has been worked out in considerable detail, especially as regards the dependence of the velocity of the ejected electron on the frequency of the absorbed light, but very little knowledge exists about the analogous phenomenon in the region of higher frequencies. A very simple method of investigating the velocities of the $\beta$-rays was used by Rutherford, Robinson, and Rawlinson.* They found that the $\gamma$-rays from radium B and C, when passed through heavy metals, such as gold or lead, caused the emission of several groups of electrons, each group consisting initially of electrons of the same velocity. They showed that this fact alone gave information about the connection between the $\beta$-rays and $\gamma$-rays of radio-active bodies, but, in addition, they made the interesting observation that the velocity of the electrons liberated from gold had 1 to 2 per cent. higher velocity than those from lead.

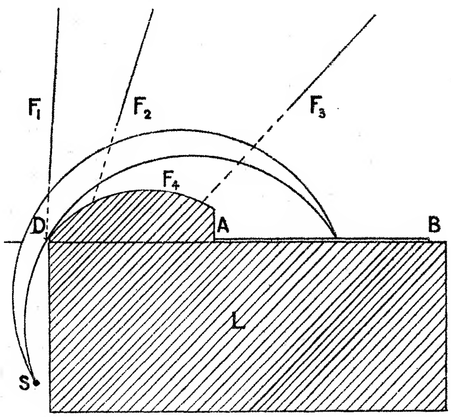
This fact receives a simple explanation if it be assumed that the energy of the emitted electron is equal to some energy characteristic only of the $\gamma$-ray, minus the energy necessary to remove the electron from the atom. The difference in the energies of the electrons ejected from gold and lead by the same $\gamma$-rays is then explained by the difference in the work of removal of these electrons from their respective atoms. Since the general relation of the gold atom to the lead atom is known, it should be possible to deduce from the experimental values for this difference in the work of removal, from what part of the atom the electron originated, and then values might be obtained for the energy characteristic of the $\gamma$-ray. The work to be described was undertaken with these points in view, the experimental determination

* 'Phil. Mag.' (2), p. 277 (1914).

consisting in the measurement of the energies of the electrons ejected from various metals by the $\gamma$-rays of radium B and C, with the special object of measuring accurately the differencies of these energies from metal to metal. As wide a range of metals as was practicable was used, in order to test any explanation of these energy differences.

*The Experimental Method.*

The experimental method used was identical with that of Rutherford, Robinson, and Rawlinson (*loc. cit.*), in which the energies of the electrons are measured by bending them in a magnetic field. By a method to be described later, a line source of the electrons to be investigated was obtained. This source, S (see fig.), was fixed about 3 mm. from the end of a lead




block, L ($10{\cdot}5 \times 4{\cdot}5 \times 3$ cm.). A comparatively wide slit, D (4–7 mm.), was arranged vertically above the source, and the latter was usually about 3·6 cm. below the slit. A photographic plate, AB, is fixed in position on the top of the lead block. The whole apparatus is lowered into a brass box and exhausted to a low vacuum. The box is then placed between the poles of a large electromagnet, which are so adjusted as to give a nearly uniform field over the space between them, the magnetic field being parallel to the source and the slit. In the uniform magnetic field, electrons of a definite velocity describe circles of the same radius, and, even with the wide slits used, the circles intersect the photographic plate along a curved line of comparatively narrow width. The existence of a group of electrons of definite velocity is thus shown by a line on the plate.

The general appearance of the photographs was the same as described by Rutherford (*loc. cit.*); the outside edges of the lines were sharp, and the radius, $\rho$, of the circular path of the rays forming this part of the trace was

determined by the formula $\rho = \sqrt{(D^2+a^2)}$, where $2a$ is the distance of the source from the slit and 2D is the distance of the outside of the line from the vertical through the top of the source. The dimensions of the apparatus are larger than that used by Rutherford, $\rho$ varying between 3 and 4·5 cm., since, although this diminishes the absolute intensity of any line, it increases the contrast against the general background. Also, slightly more elaborate screening arrangements were adopted, screens $F_1F_2F_3F_4$ of lead being used to cut down stray radiation.

The source of $\gamma$-rays, S (see fig.), was a small tube about 10 mm. long and 0·7 mm. diameter, filled with radium emanation. A thin sheet of the metal to be investigated was wrapped tightly round the tube. Radium B and C are deposited from the emanation on the walls of the tube, and the $\gamma$-rays from these passing out of the tube traverse the metal and liberate high-speed electrons from it. In this way an approximately line source is obtained, and the nearness of the radiator to the radiation gives the maximum intensity. Five elements were investigated, Ur, Pb, Pt, W, and Ba. Pb, and Pt were used in the form of foils, 0·3 mm. thick, as described; the other three were taken in the form of oxides. In this case the emanation tube was covered with a silver sheath, and a thin layer of the oxide was fixed on to the silver. Special experiments showed no intense lines were obtained from the silver.

The values of H, the magnetic field, were determined by taking photographs with the same apparatus of the natural $\beta$-ray spectrum of radium B, and using the values of $H\rho$ for these lines found by Rutherford and Robinson.* In place of the usual active wire, a plate source was used ($1 \times 0·3$ cm.). If this is tilted so that a line perpendicular to its plane passes somewhere in the region of A (see the fig.), excellent focussing is obtained. Such a source is far more convenient to prepare than an active wire.

$H\rho$ is determined experimentally, and the energy corresponding to this is obtained by means of the relativity formulæ. It is found very convenient to characterise these energies by stating the potential difference in volts an electron would have to fall through to acquire this energy.

The region investigated is that corresponding to the main $\beta$-ray emission of radium B, that is, to $\beta$-rays of speeds 0·8 to 0·6 of the velocity of light.

### *Experimental Results.*

With each of the elements, tungsten, platinum, lead, and uranium, a group of three main lines was found. Other fainter lines were present, but these strong lines will be considered first. Each group had the same general

* 'Phil. Mag.,' vol. 26, p. 717 (1913).

appearance, the only difference being that each of the three lines from a metal of smaller atomic number were shifted by the same amount in the direction of increasing energy in relation to the corresponding lines from a metal of higher atomic number. This can be seen from Table I, in which under each element are arranged the energies of the three lines comprising the group: corresponding lines for different elements are in a horizontal row.

Table I.

| Metal ..................... <br> Atomic No. ............... | Barium. <br> 56 | Tungsten. <br> 74 | Platinum. <br> 78 | Lead. <br> 82 | Uranium. <br> 92 |
|---|---|---|---|---|---|
| Energies in volts × $10^{-5}$ | — <br> 2·53 <br> — | 1·66 <br> 2·20 <br> 2·76 | 1·58 <br> 2·12 <br> 2·69 | 1·49 <br> 2·03 <br> 2·60 | 1·22 <br> 1·74 <br> 2·31 |

Thus the tungsten lines are all about 8000 volts higher energy than the platinum lines. Only one line was measured for barium, so it cannot be used in this connection.

It is clear from this that there are three distinct $\gamma$-rays acting, each being responsible for one line, and further that the energies observed can all be included in a statement as follows:—

If $E$ = energy of the ejected electron,

$W_1$, $W_2$, $W_3$, represent energies characteristic of the three $\gamma$-rays and independent of the atom acted upon, and

$W_a$ represent an energy characteristic of the atom,

then for any one element

$$E = W_n - W_a, \qquad n = 1, 2, 3.$$

For another element $W_a$ will have a different value, and a fresh group of lines will be obtained.

The obvious interpretation of $W_a$ is that it represents the energy necessary to remove the electron in question from its position inside the atom to the surface. From the magnitude of the change of $W_a$ from atom to atom (8000 volts between platinum and tungsten) it will be seen that the electrons giving these lines must come from the K rings. The energy necessary to remove an electron from the K ring is obtained from the wave-length $\lambda$ of the K absorption band by the quantum relation $E = hc/\lambda$, and is expressed in volts V by the relation $V = E/e$, where $e$ is the electronic charge.

The experimental values of the wave-lengths of the K absorption bands and the corresponding energy in volts are shown in Table II with the references.

Table II.

| Metal. | λ in Å.U. | V in volts. | References. |
|---|---|---|---|
| Barium.................... | 0·3306 | $0·373 \times 10^5$ | Siegbahn and Jönsson.* |
| Tungsten .................... | 0·1781 | 0·693 | Duane and Patterson.† |
| Platinum .................. | 0·1578 | 0·782 | Sieg and J. |
| Lead ........................ | 0·1385 | 0·891 | Sieg and J. |
| Uranium .................. | 0·1048 | 1·178 | Sieg and J. |

* 'Phys. Zeit.,' vol. 20, p. 251 (1919).
† 'Phys. Rev.,' p. 526 (December, 1920).

To each of the energies of the ejected electrons (see Table I) is now added the energy necessary to remove an electron from the K ring and the values obtained are shown in Table III.

Table III.

| Barium. | Tungsten. | Platinum. | Lead. | Uranium. |
|---|---|---|---|---|
| — | 2·35 | 2·36 | 2·38 | 2·40 |
| 2·90 | 2·89 | 2·91 | 2·92 | 2·92 |
| — | 3·46 | 3·46 | 3·49 | 3·48 |

The numbers in a vertical row represent respectively $W_1$, $W_2$, $W_3$, the energies characteristic of the γ-rays, and so the numbers in a horizontal row should be constant. This is seen to be the case with fair accuracy, but the variations are mostly in one direction. It is difficult to be sure of this as the variation is within the limit of error of measurement, and in addition there is a strong possibility of a systematic error due to the tungsten lines all being weaker and less sharply defined. In any case, unless the whole phenomenon is radically different from that pictured, this steady variation, if it exists, would be due to a slight dependence of $W_1$, $W_2$, $W_3$ on the atom in which they were absorbed. These results show definitely that the main β-ray emission under these conditions is due to three main γ-rays, and that the β-rays emitted come from the K rings.

Before treating the fainter lines it is convenient to consider the natural β-ray spectrum of radium B. Rutherford, Robinson and Rawlinson (*loc. cit.*) showed that the magnetic spectrum of the β-rays excited in lead was identical with the natural β-ray spectrum of radium B. This result was repeated in the present work. Since radium B and lead are isotopic, and as has just been shown, the emission is due to the ejection of electrons from the electronic system of the atom, this is in complete agreement with Rutherford's theory of the connection between the β-ray and γ-ray emission of radio-active atoms.

According to his view the primary phenomenon is the emission of a $\beta$-particle from the nucleus. It may happen, through some mechanism at present unknown, that this $\beta$-particle gives rise to a $\gamma$-ray. This $\gamma$-ray in traversing the electronic system of the atom may be absorbed and eject a high speed electron. It is these last electrons which constitute the $\beta$-ray line spectrum.

As a result of this present work it is possible to amplify this theory in some details. The evidence just brought shows that the three main $\beta$-ray lines originate in the K ring due to the action of three $\gamma$-rays, and proceeding in this way it can be shown that all of the faster lines of the $\beta$-ray spectrum of radium B, both strong and faint, can be accounted for by supposing that there are six $\gamma$-rays, each characterised by a definite amount of energy, and that each of these $\gamma$-rays ejects electrons from one of two definite levels in the atom. The first of these is the K ring and the second the $\Lambda'$ level* which is one of the L group. To explain the finer details of the L lines in the X-ray spectra of the elements it is found necessary to assume the existence of four distinct levels. In the order of increasing energy they are called LL′ $\Lambda\Lambda'$. Absorption bands corresponding to these levels have been obtained and their existence seems assured.

For atoms of atomic number 82 (lead, radium B) the wave-lengths of the L and L′ absorption bands were found by De Broglie† to be 0·945 Å.U. and 0·811 Å.U., and the corresponding energies to remove an electron from these levels are $0{\cdot}131 \times 10^5$ volts and $0{\cdot}152 \times 10^5$ volts. For the present purpose the L′ and $\Lambda$ levels can be considered identical and the difference of energy between the $\Lambda$ and $\Lambda'$ level is found from the magnitude of this $\Lambda$ doublet in the line spectrum (Sommerfeld‡). The energy of the level then comes to $0{\cdot}157 \times 10^5$ volts. The calculation of the radium B $\beta$-ray spectrum now proceeds as follows. The values of the $\gamma$-ray energies that are assumed are shown in column I of Table IV, column II gives the wave-length in Ångstrom units deduced from the quantum relation. The justification of this is given later.

From each of these $\gamma$-ray energies is subtracted in turn the K absorption energy ($0{\cdot}891 \times 10^5$ volts) and the $\Lambda'$ absorption energy ($0{\cdot}157 \times 10^5$ volts), and the results are shown in Table V.

* Sommerfeld, 'Atombau und Spektrallinien,' p. 180.

† Sommerfeld, *loc. cit.*, p. 206.

‡ Sommerfeld, *loc. cit.*, p. 186.

Table IV.—$\gamma$-rays of RaB.

| I. | II. |
|---|---|
| Energies in volts. | $\lambda$ in A.U. |
| $4 \cdot 000 \times 10^5$ | 0·0308 |
| 3·639 | 0·0339 |
| 3·492 | 0·0354 |
| 2·918 | 0·0423 |
| 2·529 | 0·0488 |
| 2·385 | 0·0519 |

Table V.—$\beta$-ray Spectrum RaB.

| I. | II. | III. | IV. |
|---|---|---|---|
| Origin of Line. | Intensity. | Energy observed. | Energy calculated. |
| | | volts. | |
| $\Lambda'$ | *f.* | $3 \cdot 851 \times 10^5$ | $3 \cdot 843 \times 10^5$ |
| $\Lambda'$ | *m.s.* | 3·473 | 3·482 |
| $\Lambda'$ | *s.* | 3·328 | 3·335 |
| K | *v.f.* | 3·103 | 3·109 |
| $\Lambda'$ } K } | *m.s.* | 2·756 | { 2·761 { 2·748 |
| K | *v.s.* | 2·608 | 2·601 |
| $\Lambda'$ | *m.* | 2·364 | 2·372 |
| $\Lambda'$ | *m.s.* | 2·227 | 2·228 |
| K | *v.s.* | 2·031 | 2·027 |
| K | *m.s.* | 1·645 | 1·638 |
| K | *v.s.* | 1·494 | 1·494 |

Column I shows the origin of the line, column II the relative intensity, column III the observed energy, column IV the calculated energy. The observed energies are slightly different from the values given in the original paper, since newer values of the constants have been used. They were calculated afresh from the experimentally determined $H\rho$'s.

The agreement is seen to be well within the experimental error (1/300), also all the lines are given without any gaps and no extra ones are predicted. Of course, three of the $\gamma$-rays are the same that gave the groups of lines first discussed, but the values obtained from the radium B lines will be used, since these measurements are more accurate.

This explanation of the radium B $\beta$-ray spectrum might seem forced in one particular, in that half of the lines are supposed to originate in the $\Lambda'$ level, a level that from X-ray work seems one of the less important of the main L group. But evidence can be brought to show that under certain

circumstances the $\Lambda'$, $L'$, and L levels can all be detected, and that the lines originating in the $\Lambda'$ level are the strongest. This evidence is obtained from a study of the low velocity $\beta$-rays from thorium D. These lines have been measured by Hahn,* who found a strong line of velocity 0·29 and a weaker line of velocity 0·38. It is possible to obtain much greater detail with the focussing arrangement, and seven lines have been measured by the writer in this region. There are three main groups, each group consisting of a strong line with companions. The values obtained are shown in Table VI; column 1 gives the value of $H\rho$, column 2 the intensity, column 3 the corresponding energies, column 4 the level from which the $\beta$'s originate, and column 5 the calculated energies. Three $\gamma$-rays of characteristic energies $0{\cdot}412 \times 10^5$ volts, $0{\cdot}532 \times 10^5$ volts, and $0{\cdot}564 \times 10^5$ volts are postulated, and the values for the energies of the $\Lambda'$, $L'$, and L ring are taken as those for a body of atomic number 82, that is, respectively, $0{\cdot}157 \times 10^5$, $0{\cdot}152 \times 10^5$, and $0{\cdot}131 \times 10^5$ volts.†

Table VI.—$\beta$-rays ThD.

| 1. | 2. | 3. | 4. | 5. |
|---|---|---|---|---|
| $H\rho$. | Intensity. | Energy observed. | Origin of line. | Energy calculated. |
| | | volts. | | |
| 543 | *v.s.* | $0{\cdot}254 \times 10^5$ | $\Lambda'$ | $0{\cdot}255 \times 10^5$ |
| 550 | *s.* | 0·261 | $L'$ | 0·260 |
| 570 | *m.* | 0·280 | L | 0·281 |
| 663 | *v.s.* | 0·375 | $\Lambda'$ | 0·375 |
| 674 | *m.* | 0·400 | L | 0·401 |
| 690 | *s.* | 0·406 | $\Lambda'$ | 0·407 |
| 696 | *m.s.* | 0·412 | $L'$ | 0·412 |

The agreement is seen to be good, but there are several points to notice. Firstly, the lines from the $\Lambda'$, $L'$, and L levels are in the order of decreasing intensity, thus the third line from the hardest $\gamma$-ray was not found, probably because it was too faint. Secondly, these $\gamma$-rays are too soft to eject electrons from the K ring, but all the levels of the L group have been found (the $\Lambda$ level would be quite indistinguishable from the $L'$ level). The reason why the $L'$ line was not found in the 663 $H\rho$ group is because the extreme intensity of the 663 line would mask a close companion line.

These measurements are given here to show, from the point of view of the

* 'Phys. Zeit.,' vol. 12, p. 273 (1911).

† It is not known whether these $\beta$-rays are emitted by ThC (83) or ThD (81). In either case there is no doubt that the electrons originate from the levels given.

ejection of electrons by γ-rays, that the $\Lambda'$ level is the most important one of the L group, and, therefore, the position given to this level in the explanation of the natural β-ray spectrum of radium B is justified.

From the results given, it is seen that the magnetic spectrum of the high-speed electrons excited by γ-rays in metals like platinum or uranium is exactly similar to the natural β-ray spectrum of radio-active bodies, the only difference being that the same radio-active atom which produces the γ-ray also probably absorbs it. Further, the main lines of the phenomenon are sufficiently described by combining with the known electronic structure of the various atoms, the assumption of certain γ-rays characterised by definite amounts of energy.

The faint lines, previously mentioned, that were observed from W, Pt, Pb, and Ur, all fall under this scheme, but it is difficult to make the measurements accurately, owing to the faintness of the lines, and it is not considered worth while giving the values.

### *Discussion of Results.*

Evidence has been brought to show the existence of several γ-rays, each γ-ray characterised by a certain energy which is set free when it is absorbed. On the basis of the quantum theory, one would expect this energy to be $h\nu$, where $\nu$ is the frequency of the radiation. In this way the wave-lengths of these γ-rays can be calculated, and the values obtained are shown in column 2 of Table IV. These wave-lengths are shorter than any measured by Rutherford and Andrade, but γ-rays of higher frequency are known to be present. Rutherford,* from considerations of the absorption coefficients of γ-rays compared to absorption coefficients of X-rays generated at high voltages, showed that the wave-lengths of the main γ-rays were much shorter than had previously been supposed, and that the hardest γ-rays of radium C might be of the order 0·007 Å.U. His general results also pointed to the fact that the groups of β-rays are due to the transformation of the energy of the γ-rays in single quanta, according to the relation $E = h\nu$.

It is seen therefore, that there is good evidence to believe that the wave-lengths are right, but it should be pointed out that small corrections may have to be applied in the light of later work. In this deduction it is assumed that the law

$$\text{Energy of the electron} = h\nu - w_0$$

is exact. This has been proved to hold with considerable accuracy for light, but in the true equation there may be small correction terms which, while

* 'Phil. Mag.,' vol. 34, p. 153 (September, 1917).

quite negligible for low frequencies, may have an effect when the frequency is ten thousand times greater. It may be that the phenomenon is not correctly described by an energy equation at all, and owing to the small variation of atomic number that was practicable, these experiments were unable to test this point. It is always possible, owing to the simpler relations that all dynamical quantities bear to each other at low speeds, compared to the same relations at high speed, that the energy expression might be quite accurate at low frequencies but in error at high ones. These points could be tested if the wave-lengths of the $\gamma$-rays from thorium D could be measured, and, although they are short, this should be possible by Rutherford's transmission method. If the values calculated from the characteristic energies obtained from the $\beta$-ray spectrum agreed with the values found directly it would show that the corrections considered above are not serious.

Owing to the meagre material it is not thought advisable to discuss the numerical values at this stage, but it is interesting to note that part at least of the $\gamma$-radiation is monochromatic. It has been found possible to connect these $\gamma$-rays of radium B with the $\gamma$-rays measured by Rutherford and Andrade by the crystal method, and by means of this fact it can be shown that it is probable that the quantum dynamics holds for that part of the atom from which these $\gamma$-rays come. This evidence will be given in detail later.

The different intensities of the lines present points of great interest, for in all cases it is the most firmly bound electron which gives the most intense lines. The hard $\gamma$-rays of radium B are much more absorbed by the K electrons than by the L group, and the peripheral electrons have a comparatively negligible effect. This is seen very clearly in the thorium D lines, the strongest lines come from the A′ level, the next strongest from the L′ level, and the weakest from the L level. Even these much softer $\gamma$-rays appear to have little effect on the outer electrons.

The results as a whole suggest that the chance of an electron absorbing $\gamma$-radiation depends on the relation between the energy of the binding of the electron and the energy characteristic of the $\gamma$-ray, and that the probability of absorption becomes very small when the energy of the binding is small compared to the $\gamma$-ray energy.

It is intended to continue this work by investigating the magnetic spectrum excited in metals by the hard $\gamma$-rays of radium C and the softer $\gamma$-rays of radium B.

When this work was completed my attention was directed to some recent publications of De Broglie* on the velocities of electrons set free from metals by X-rays. Quantitative results have not yet been given, but apparently the

* 'Comptes Rendus,' Nos. 5, 9, and 12, vol. 172 (1921).

effects observed are of the same general type that have been described in this paper.

*Summary.*

1. The magnetic spectrum of the $\beta$-rays excited by the $\gamma$-rays of radium B in Ur, Pb, Pt, W, and Ba, has been measured.

2. It is shown that the main lines are formed by electrons ejected from the K ring by definite $\gamma$-rays, each $\gamma$-rays being characterised by a certain energy.

3. The magnetic spectrum of the $\beta$-rays of radium B is accounted for on this basis.

4. The magnetic spectrum of the low velocity of $\beta$-rays of thorium D has been measured and is explained in the same way as the radium B $\beta$-ray spectrum.

5. On the basis of the quantum theory the wave-lengths of the $\gamma$-rays of radium B are calculated from the characteristic energies found.

6. Evidence is given to show that the greater the energy of binding of an electron the greater is the probability of it absorbing this hard $\gamma$-radiation.

In conclusion I would like to express my indebtness to Prof. Sir Ernest Rutherford, who suggested the problem and the method of attack, and directed the whole course of the work. My thanks are due to Mr. G. R. Crowe for the preparation of the active sources used.

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